A Month Off

Migrating a Robot Controller from the Proprietary INtime RTOS to Linux

CLOOS

Weld your way.

www.cloos.de

About me

- Born in the 70s with a fascination for electronics and computers
- German ”Diplom Ingenieur” since 1997
- First job in industrial automation
- Did embedded linux systems for 17 years
- Joined Cloos robot controller team in 2019
- Married, three kids

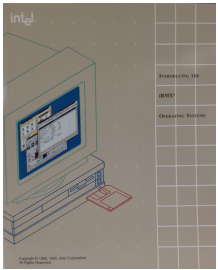
What is this talk about?

- Cloos is a manufacturer of industrial robots
- In 2021 we decided to do a study on porting the robot controller from the proprietary INtime RTOS to Linux/Preempt-RT
- This is about our experience on the way and what we learned from it

Robotics at Cloos

- Building robots since 1981
- Inhouse designed robot controller based on Intel processors since 1986
- Using the PL/M programming language and custom RTOS
- 1995: First robot controller based on PC hardware in industry

TenAsys INtime RTOS history

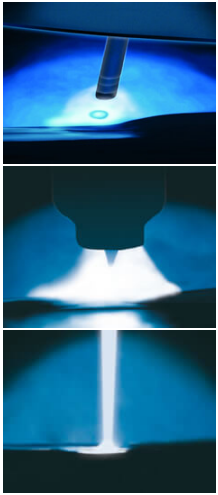


Radisys

tenAsys

- Started as Intel RMX in the 1970s to create demand for their processors
- In 1996 RadiSys acquired the iRMX/INtime RTOS technology
- INtime 1.0 was originally introduced in 1997 in conjunction with Windows NT
- TenAsys company was founded in 2000 as a spin-off of RadiSys Corporation

Processes at Cloos

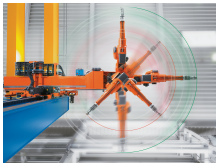


- Welding processes for manual and automated applications
  - Gas shielded metal arc welding
  - Tungsten inert gas welding
  - Laser welding
- Plasma and laser cutting
- Grinding

What is inside a robot controller?

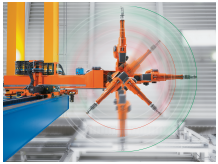
- Industrial PC with a custom PCI card providing digital and analog I/O, plus CAN-Bus
- PC is EtherCAT master using a standard Ethernet controller
- Servo drives for all connected axes (up to 32) are EtherCAT slaves

Realtime requirements



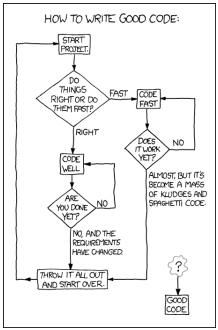
- Axes run in cyclic synchronous position mode (CSP)
- Must provide a target position for each axis every buscycle (typical 1-4ms)
- Motion planner does all calculations in a multiple of the busclock (typical 8ms)
- Interpolation between motion planner clocks in software

Realtime requirements



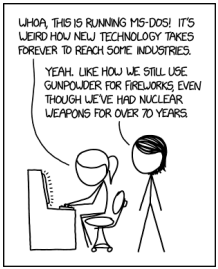
- Torque Feedforward values based on dynamic model to help speed controller
- Adapt speed controller gain depending on load
- Consider values from sensors to adapt motion

The codebase



- About 3 million lines of sourcecode
- Started in the 80s in PL/M
- later converted to C
- mostly still compatible to Intel C386 compiler (ANSI C) from 1997
- split in different processes that communicate via shared mem and semaphores
- Legacy MFC-GUI
- New Qt-GUI, not feature complete, still depends on legacy GUI

The codebase

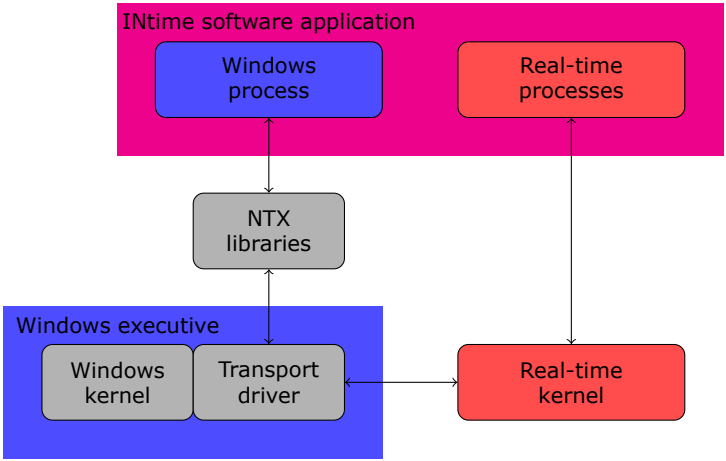


- Lots of technical debt
- Knowledge encoded from people that have left long time ago
- Will have to support legacy systems for decades (we still support building with Intel C386 from 1997)
- Carefully refactoring little by little

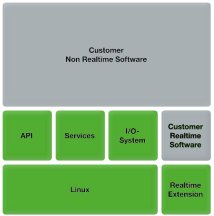
TenAsys INtime RTOS technology

- Separate, independent kernel outside of the Windows kernel
- Schedules all real-time processes to run first, at a higher priority than Windows
- Windows application threads communicate with their real time counterparts on the INtime kernel via NTX-API

TenAsys INtime RTOS diagram

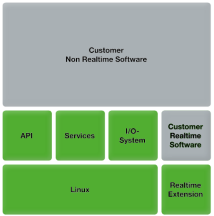


Keba flexcore



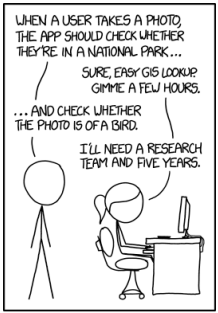
- In 2021 we got a tempting offer from Keba, an automation solutions supplier
- Keba D3 controller is an automation controller running Linux
- Debian buster ia32 with Preempt-RT kernel
- Integrated safety solution suitable for robotics
- Flexcore means you can run your own realtime applications besides the Keba application

Benefits



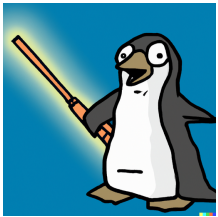
- Safety problem is solved
- Using off the shelf hardware
- Only one controller, no inter-device communication required
- Getting rid of license fees: Windows, INtime and EtherCAT Master

How far can we get in 6 weeks?



- How could we find out, if it would be possible to run our system on Keba Flexcore?
- Theoretical evaluation is hard
- I came up with the idea to do a study and see how far we can get in six weeks.
- All the realtime and GUI developers would work fulltime on this
- To my amazement, everybody agreed

Don’t use force, Luke

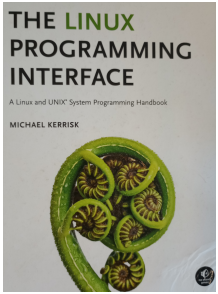


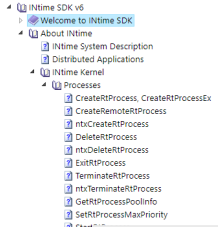
- The robot controller team members are experts with decades of experience
- Honor that
- Forcing anybody to use Linux would break motivation
- Involve everybody in the team in the decisionmaking process
- Make sure the decision is open

Comfort

- Consider that this is whole new world for the team, outside their comfort zone
- Make sure everbody gets the time to make himself familiar
- Give support wherever you can, there are no stupid questions
- Don’t make fun of anyone
- Encourage and join the fun when progress happens
- Make the environment as comfortable as possible

Where to get help?





- When in doubt, consider Kerrisk
- http://support.tenasys.com/intimehelp
- Axel Scholz, my knowledgeable colleaque who is doing INtime and its predecessors since the 80s and has seen a lot
- We did the API implementation together

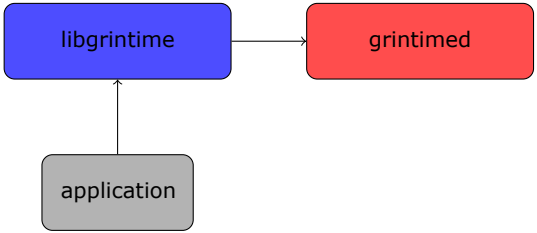
Concept

- Implement the API completely in userspace as a shared library
- Since the INtime application will have to be built from the same codebase, inflict as few changes as possible
- Only implement the part of the API that we are actually using
- grintime - **g**eneric **r**eimplementation of the **INtime** API

How to get started?

- Build the application without linking the INtime libs
- See what functions are missing
- Start implementing ;)
- Use a 32-Bit Debian Buster VM for building and testing
- Evaluate Visual Studio CMake-based linux builds to support the GUI team

Grintime topology



INtime object directories

- Resources like process, thread, semaphore are objects with unique 16-Bit id (`RTHANDLE`)
- Object directory is a per process key/value store where the key is a string and the value is the 16-Bit id
- Access to the object directories is global, so can be used for IPC

Object directory API

- `BOOLEAN CatalogRtHandle(RTHANDLE process, RTHANDLE object, LPCSTR name)`
- `RTHANDLE LookupRtHandle(RTHANDLE process, LPCSTR name, DWORD milliseconds)`
- `BOOLEAN UncatalogRtHandle(RTHANDLE process, LPCSTR name)`

Linux system object implementation

- Object array is stored in shared memory
- libgrintime maps this memory in main()
- any object create/delete is registered there
- Each process maps this memory
- Getting the object from a 16 bit id can be done in realtime

Object structure

```
struct system_object
{
    bool enabled;
    union {
        struct process_type process;
        struct thread_type thread;
        struct segment_type segment;
        struct heap_type heap;
        struct semaphore_type semaphore;
        struct mailbox_type mailbox;
        struct file_type file;
    };
    WORD object_type;
};
```

Setting up shared memory

```
off_t size = sizeof(struct system_object) * SYSTEM_OBJECT_COUNT;
int flags = create_shm ? O_CREAT | O_EXCL : 0;

fd = shm_open(SYSTEM_OBJECT_SHM_NAME, flags | O_RDWR, S_IRUSR |
    S_IWUSR);
if (fd == -1)
    exit(1);

if (create_shm && (ftruncate(fd, size) == -1))
    exit(1);

system_objects = mmap(NULL, size, PROT_READ | PROT_WRITE,
    MAP_SHARED, fd, 0);
if (system_objects == MAP_FAILED)
    exit(1);
```

Linux object directory

- The directory itself is implemeted as a std::map
- The key is a pair of process id and object name
- The value is the object id
- Implemented as a gRPC service in grintimed
- Querying the directory is not a realtime operation

Process API

- `RTHANDLE CreateRtProcess(LPCSTR filename, LPCSTR arguments, const LPPROCESSATTRIBUTES attributes, DWORD flags)`
- `BOOLEAN DeleteRtProcess(RTHANDLE process, DWORD flags)`
- `BOOLEAN WaitForRtProcess(RTHANDLE process, DWORD milliseconds, DWORD *exit_code)`
- `VOID ExitRtProcess(VOID)`

main()

- main()-function in libgrintime
- Setup RT-scheduling and prio, signal handler and memory allocator
- No changes to codebase required
- To deal with the existing main(), we add `-Dmain=main_grintime` to the Compiler commandline

Creating a new process

```
switch (child_pid = fork()) {
case -1: /* fork() failed */
    ... Error handling ...
    return BAD_RTHANDLE;
case 0: /* Child of successful fork() comes here */
    sem_wait(sem);
    printf("returns %d\n", execv(filename, argv)); /* Never
       returns on success; returns -1 on error */
    return BAD_RTHANDLE;
default:
    hdl = register_process(child_pid, basename(filename));
    sem_post(sem);
    set_status_code(E_OK);
    return hdl;
}
```

Thread API(excerpt)

- `RTHANDLE CreateRtThread(BYTE priority, LPPROC entry, DWORD stack_size, LPVOID parameter)`
- `BOOLEAN DeleteRtThread(RTHANDLE thread)`
- `BYTE GetRtThreadPriority(RTHANDLE thread)`
- `BOOLEAN SetRtThreadPriority(RTHANDLE object, BYTE priority)`
- `BOOLEAN SuspendRtThread(RTHANDLE thread)`
- `BOOLEAN ResumeRtThread(RTHANDLE thread)`
- `BOOLEAN RtSleep(DWORD milliseconds)`
- `VOID knRtSleep(DWORD kernel_ticks)`

Suspend/Resume

- Found no concept for `SuspendRtThread()` and `ResumeRtThread()` in linux
- So we implemented it using per thread signal handler
- Using syscall `tgkill` to send the signal to a thread
- Not in glibc, so this seems a little hacky
- Comments welcome

Thread priorities

- INtime thread priorities range from 0(highest) to 254
- Linux realtime scheduler priorities range from 99(hightest) to 1
- Fix this with lookup table, which is application specific

Semaphore API

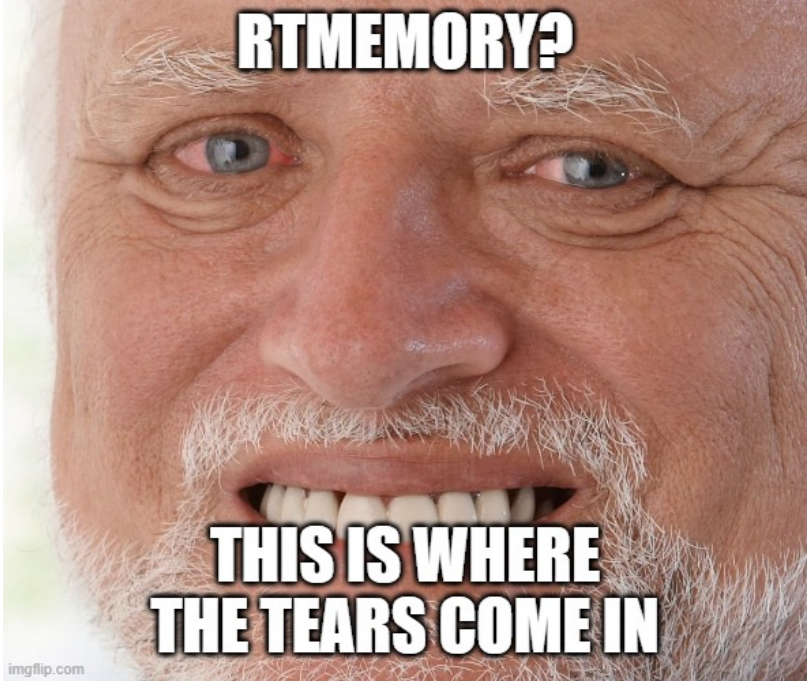
- `RTHANDLE CreateRtSemaphore(WORD init_count, WORD max_count, WORD flags)`
- `BOOLEAN DeleteRtSemaphore(RTHANDLE semaphore)`
- `DWORD WaitForRtSemaphore(RTHANDLE semaphore, WORD unit_count, DWORD milliseconds)`
- `BOOLEAN ReleaseRtSemaphore(RTHANDLE semaphore, WORD release_count)`

Implemenation details

- Not much to see here
- Decided to go with Posix semaphores which means we can only use count ”1”
- Matches our application
- To support other count values, we would need to go with System V semaphores
- You always have to leave some room for improvements in the future

Memory API(excerpt)

- `PVOID AllocateRtMemory(DWORD size)`
- `DWORD FreeRtMemory(PVOID offset)`
- `RTHANDLE CreateRtMemoryHandle(PVOID offset, DWORD size)`
- `BOOLEAN DeleteRtMemoryHandle(RTHANDLE segment)`
- `PVOID MapRtSharedMemory(RTHANDLE segment)`
- `BOOLEAN ReleaseRtSemaphore(RTHANDLE semaphore, WORD release_count)`
- `DWORD GetRtPhysicalAddress(PVOID offset, DWORD size, DWORD _reserved)`
- `PVOID MapRtPhysicalMemory(DWORD abs_addr, DWORD size)`


RTMEMORY?
THIS IS WHERE
THE TEARS COME IN
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Shared memory

- In INtime, all heap memory can simply be used as shared memory
- With POSIX shared memory objects this is not that easy
- Use a custom allocator
- dlmalloc can be configured to use mmap for allocations
- Allows to define a custom mmap function
- Keep track of all allocations in case they will be mapped later

Implementing MMAP for dlmalloc

```
ftruncate(shm_fd, shm_size + page_aligned_size);

mmap(NULL, page_aligned_size, PROT_READ | PROT_WRITE, flags,
    shm_fd, shm_size);

allocations[allocation_idx].ptr = ptr;
allocations[allocation_idx].size = size;
allocations[allocation_idx].offset = shm_size;
allocations[allocation_idx].mapped = false;
allocation_idx++;

shm_size += page_aligned_size;
```


ONE DOES NOT SIMPLY
MAP A PHYSICAL ADDRESS FROM USERSPACE
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Physical memory

- In INtime you can map physical memory addresses using `MapRtPhysicalMemory()`
- To my horror this was used in our application IPC
- The physical address of a data structure was sent to another process and used there
- We started implementing this using the `pagemap` of the sending process and `/dev/mem`
- Decided this was such a bad design decision originally that we fixed it in the application using shared mem

Achievements

- INtime helloworld example is working
- Cloos main realtime applications are starting up
- GUI project files have been ported to CMake
- Lots of windows dependencies removed

Lessons learned

- Doing a study was a good approach to the problem
- Porting a RTOS API can get quite addictive, I have spent every free minute there
- Pay respect to people and you can achieve amazing things
- Microsoft has done an amazing job in supporting Linux development from Visual Studio
- There’s still some rough edges though

Consequences

- All developers involved voted for continuing the Linux/Flexcore approach
- Component crisis hit us hard, had to suspend porting and spent the last year adding new hardware support
- grintime will be opensourced so everybody can join the fun
- Follow `https://github.com/grintime` to keep posted